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Video-Supervised Classification of Sonar Data for Mapping Seafloor Habitat

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Abstract

A new raster map product called a "seafloor character map" has been developed to describe benthic habitat, and will be produced as part of a suite of products for the California Coast State Waters Mapping Project. The map resolution is identical to that of the sonar data from which it is derived and preserves the gradational qualities of the substrate in a marine environment unlike map products based on delineated polygonal regions. Each pixel is given a value, through a supervised numerical classification method groundtruthed by seafloor video observations. The classification combines information about bottom hardness, rugosity, slope, and depth based on current standards used in California fisheries management. Both the GIS layer and a digital map image will be published as part of a folio that will also include the sonar and video observation data, derived images of the data, and traditional geologic and habitat interpretations.

Introduction

The morphology, lithologic composition, and bathymetric texture of the seafloor are recognized as being important elements in determining the distribution and abundance of many benthic and demersal species (Carlson and Straty 1981, Love et al. 1991, Stein et al. 1992, Krieger 1993, McConnaughey and Smith 2000, Rooper and Zimmermann 2007). Sonar data–based seafloor maps have gained broad acceptance as a means to map the lithologic and morphologic character of the seafloor (Mayer et al. 1999, Todd et al. 1999, Kostylev et al. 2001, Cochrane and Lafferty 2002, Dartnell and Gardner 2004). The California Coast State Waters Mapping Project (CCSWMP) is at present mapping California state waters out to 3 nautical miles from shore. CCSWMP is managed by the California Ocean Protection Council through the California Coastal Conservancy, and is funded in part by California State Proposition 84 of 2006. A consortium of government and private agents has been assembled to acquire the data and produce maps including Fugro Pelagos Inc., the California State University Monterey Bay Seafloor Mapping Lab, Moss Landing Marine Labs Center for Habitat Studies, and the USGS Coastal and Marine Geology Program. For maps covering such a large contiguous area a consistent and reproducible classification method is required. Hand drawn interpretations are not reproducible because they are subjective, especially in areas of subtle transition from one substrate class to another. Automated methods are reproducible and preferable but suffer inaccuracy due to the unavoidable variation in data quality from environmental and operational vagaries that occur during large surveys. Generally, for automated interpretation, groundtruth-supervised numerical classification of derivatives of sonar data is used such as local Fourier histogram features (Cutter et al. 2003, Intelmann et al. 2007), gray-scale covariance texture indices (Cochrane and Lafferty 2002), bathymetric position index (Lundblad et al. 2004), and bathymetric variance (Dartnell and Gardner 2004, Iampietro et al. 2004, Harney et al. 2006).

The California State Marine Life Protection Act (MLPA) calls for protecting representative types of habitat in different depth zones and environmental conditions. A science team, assembled under the auspices of the California Department of Fish and Game (CDFG), has identified seven habitats in California state waters that can be classified using sonar data and seafloor video techniques. These habitats include rocky reefs, intertidal zones, sandy or soft ocean bottoms, underwater pinnacles, kelp forests, submarine canyons, and seagrass beds. The science team also identified five depth zones, which reflect changes in species composition: intertidal, intertidal to 30 m, 30-100 m, 100-200 m, and deeper than 200 m (CDFG 2007).

The CDFG habitats, with the exception of depth zones, can be thought of as a subset of a broader classification scheme of Greene et al. (1999) that is used by the U.S. Geological Survey (USGS) seafloor mapping and benthic habitat studies project (Cochrane et al. 2003, 2005). These map products are generalized polygon shape files with the Greene attributes. A Coastal Map Development Workshop, held by the USGS in 2007, identified the need for less generalized raster products that preserve some of the transitional character of the seafloor when substrates are mixed and change gradationally. The challenge addressed in this paper is developing a map/GIS product that can be produced in a consistent manner from data of variable quality that covers a large region. This paper presents methods and a modified Greene et al. (1999) seafloor classification scheme to generate maps that convey seafloor information useful to fisheries managers. The methods will likely be modified to some degree after the writing of this paper. The map will be called a Seafloor Character Map and will be one of a folio of digital maps in an online publication that includes a report and GIS.

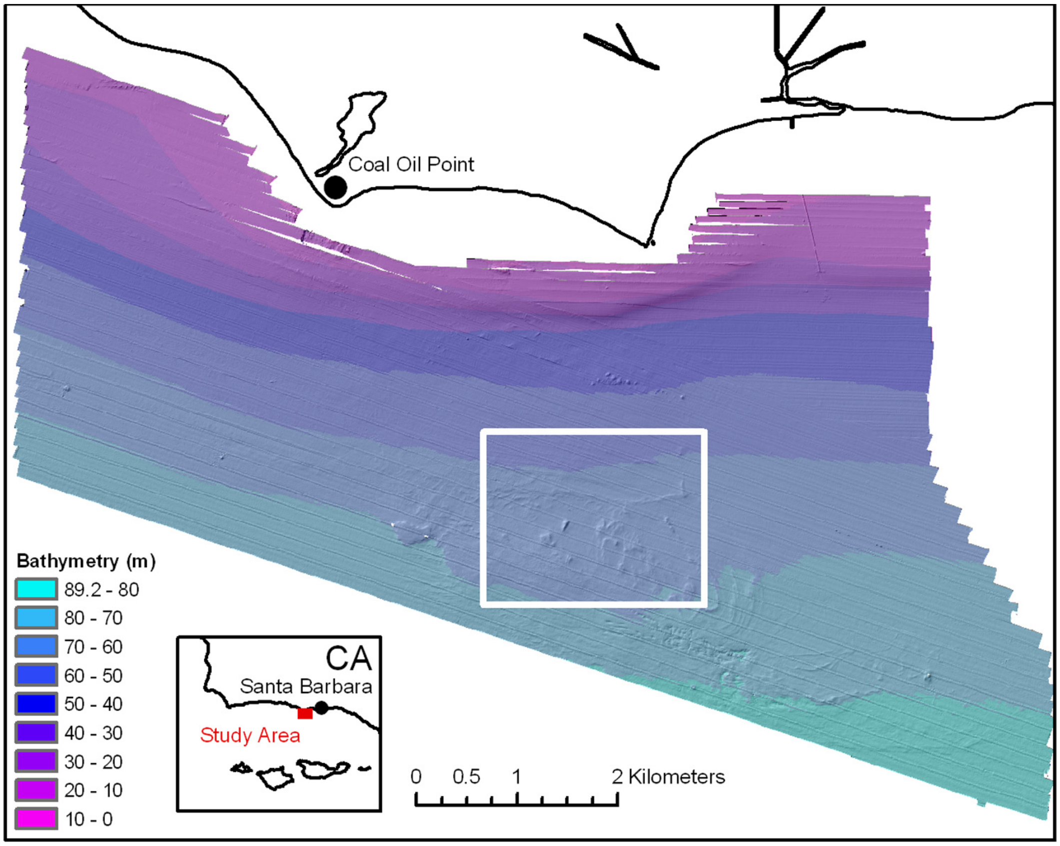

Figure 1. **Map showing area of sonar survey off Coal Oil Point, west of Santa Barbara, California, as part of the CCWSMP. Image shows color-coded water depth in meters draped over shaded relief. White box outlines the 21 km² study area shown in detailed Figs. 2 and 4.**

Data

Sonar bathymetry and backscatter-intensity rasters are the data used to produce the Seafloor Character Map and other numerical classifications of seafloor substrate (Kostylev et al. 2001, Lathrop et al. 2006, Ierodiaconou et al. 2007). Data quality within a survey is often highly variable and not necessarily optimized. Data quality for habitat mapping can be improved by reducing ship speed, discontinuing acquisition in rough seas, increasing the overlap of swaths to eliminate nadir, and eliminating any acquisition settings that would prevent normalization of backscatter values. The first three of these quality assurance measures must be balanced against survey budget constraints. The latter measure is more related to survey goals, operator capability and sonar equipment, and processing software capability. Backscatter intensity data from surveys that are designed to produce bathymetric maps often suffer from frequent changes to system settings for the purpose of optimizing the depth data. Sonar technology and data processing methodology are advancing rapidly such that variation in backscatter intensity may be correlated directly to seafloor properties (Fonseca and Mayer 2007) for surveys using systems that have been painstakingly assembled and calibrated.

This paper presents methods that were used to classify a 21 km² section of data collected for the CCSWMP in the Coal Oil Point area of the Santa Barbara Channel, California (Fig. 1). The data were collected with an interferometric sidescan sonar system. Sidescan sonars and multibeam sonars that allow time series sampling of intensity values (e.g., snippets) produce higher resolution backscatter imagery than multibeam sonars that produce a single backscatter value for each beam (de Moustier 1986). Interferometric sidescans employ multiple parallel receivers to generate phase-shift data for estimation of acoustic signal angles that are required, along with travel-time and velocity, to calculate depth. During the survey, changes in system settings were limited to those required to counter attenuation of signal with increased water depth. Most data for the CCSWMP will be acquired using multibeam sonars; overlap of swaths will not be great enough to cover nadir.

During data processing, normalization of the backscatter intensity values, to remove attenuation loss, was accomplished through a process generally referred to as flat-fielding. Flat-fielding is an empirical gain-normalization method wherein individual intensity values are divided by the mean of all intensity values recorded at that range and depth during the survey. This approach is an improvement over time-varying gain correction, which ignores variation in sonar performance as a function of elevation angle. Neither method compensates for seafloor slope effects, nor for changes to system settings, though flat-fielding can compensate for system setting changes if they are applied consistently during acquisition. To maintain the best representation of seafloor backscatter-intensity variance, and bathymetric variance in the data, the individual processed swaths were mosaicked without averaging values where there is overlap of swaths in the far range. Averaging the overlap areas would result in a value that is never representative because the bottom is inhomogenous and reflects sound differently when insonified from different directions, and there is error in sonar motion and position that cannot be compensated for. The swaths were masked such that highest quality data in the overlap area were preserved in the mosaic.

Groundtruthing

To groundtruth the sonar data the CCSWMP uses a camera sled system designed by the USGS and a survey methodology developed through a joint NOAA Fisheries and USGS postdoctoral study (Anderson et al. 2007). In this method, groundtruth transects are selected to cover all areas of seafloor character based on visual inspection of the completed bathymetry and backscatter intensity data. During a transect a geologist and a biologist observe a 10 second segment of video once every minute and record seabed attributes observed during the 10 seconds, including primary substrate, secondary substrate, abiotic complexity (visually estimated rugosity), slope, biotic complexity, and biocoverage. Visual estimates of complexity and slope are subjective, represent broad classes based on Greene et al. (1999), and are used only qualitatively for supervision of the numerical classification discussed below. Additional observations of key species and geologic features are also recorded when they are observed. Tracking systems have been used to locate observations of the seafloor made by remotely operated vehicles (ROVs) with an accuracy of 5 m (Ierodiaconou et al. 2007). The camera sled positions obtained for this study were not of sufficient accuracy to georeference observations to narrow features such as the rock outcrops seen in the northwest corner of the study area (Area D, Fig. 2). In Fig. 2 the video observations are represented by a circular area with a 20 m radius, representing the uncertainty in position and the ground distance covered during the 10 second window of observation.

Based on video groundtruthing, the Coal Oil Point area is continental shelf covered predominantly with a mixture of mud and sand sediment. Based on previous geologic mapping, rock outcropping in the area is composed of layered sedimentary rock (Vedder et al. 1987) that has undergone folding, faulting, and differential wave erosion (Isaacs 1981), followed by inundation during the current high sea level epoch. Sedimentary layers composed of more indurated and less easily eroded rock form high ridges between which the more easily eroded rock is often covered with a thin veneer of coarse sediment (Cochrane and Greene, unpubl.) Despite their subtle expression in bathymetric data, these dipping, differentially eroded sedimentary rock outcrops provide habitat for a variety of rockfish species (Love et al. 2006).

The study area (Fig. 2) is representative of continental shelf along the California coast where the seafloor substrate gradates between narrow outcrops of rugose rock, to flat areas of rock and coarse sediment, to soft areas with mixtures of sand, shell hash, and silt. Video transect A (Fig. 2) is an example where there appears to be good correlation between observed substrate and backscatter intensity, mud correlated to low backscatter intensity, and rock associated with high backscatter intensity. Video transect B is situated over sonar nadir which is often low-quality sonar data, and will be used as an example of overestimation of rocky habitat, when using numerical classification, due to linear bands of high rugosity that result from noise that dominates the nadir. Transect D crosses narrow, linear, discontinuous outcrops of sedimentary rock. Transect D illustrates the problem of hand interpretation across rapidly changing substrate when the error in position (20 m, Fig. 2) is approximately the same as the substrate patch dimensions. There is no 10 second observation where the primary and secondary substrate are both rock. Transect C has one observation where both the primary and secondary substrate are rock, and was used for supervision of the numerical classification of the data.

Classification method

Maximum likelihood classification (MLC) is the supervised numerical classification method used by the CCSWMP to generate substrate maps from sonar and video data. In MLC the variance and covariance are calculated for a stack of sonar data layers and derivatives of those data. The minimum variant stack for MLC is backscatter intensity and rugosity. The MLC is supervised using statistics from signatures, small areas of the data set selected subjectively based on the video groundtruthing. Signatures for three substrate classes described by Cochrane and Lafferty (2002) are created that correspond to combinations of Greene et al. (1999) bottom induration (hard, mixed, soft) combined with rugosity calculated from bathymetry data using the method of Jenness (2003). The CCWSMP uses rugosity for seafloor complexity, rather than standard deviation (Greene et al. 1999) or other statistical values (Dartnell and Gardner 2004) that express the range of values in a neighborhood of pixels, because rugosity differentiates rough seafloor from smooth-sloping seafloor.

The classes are flat-soft, mixed, and rugose-hard; flat-soft and rugose-hard represent the two substrate classes in the California MLPA (soft and rock). The mixed class is coarse sediment and low-relief rock with high backscatter intensity and low to average rugosity. MLC signatures contain the mean value of each variant in the substrate classes rather than defining each class on ranges of values, as is done in hierarchical classification approaches that rely on backscatter intensity data that are calibrated so that values are

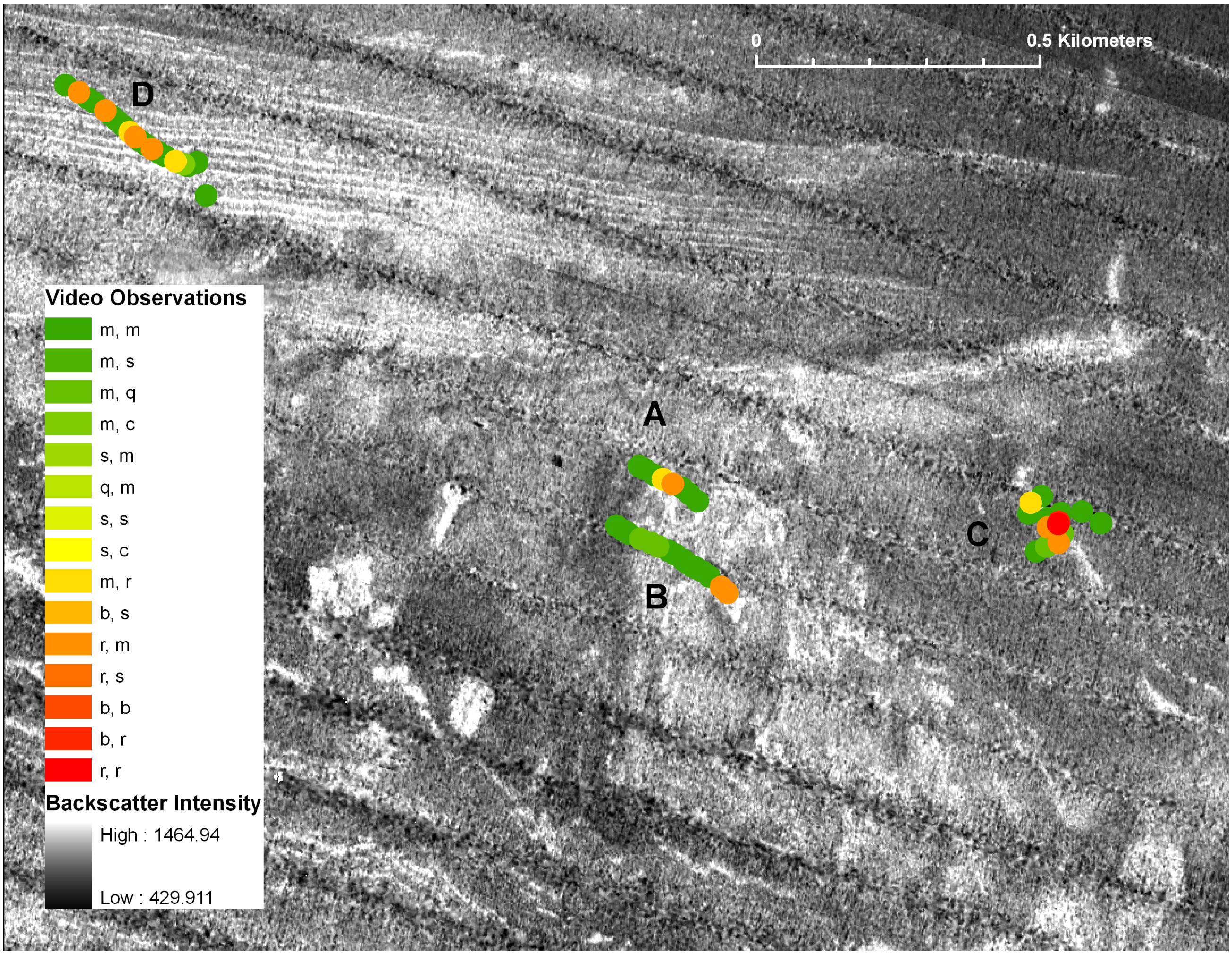

Figure 2. Image showing seafloor backscatter intensity data in the study area. High backscatter intensity is indicative of hard or rough surfaces. Letters A-D identify seafloor-video groundtruthing transects. Individual dots are observation locations (approximately 1 per minute of video transect) and are colored based on primary and secondary substrate attributes: m = mud, s = sand, q = shell, c = cobble, b = boulder, r = rock, from Greene et al. (1999). The diameter of each dot is 20 m, representing the uncertainty in position and the distance traveled during the 10 second window of video the observations are based on.

strongly correlated to substrate. The use of MLC with covariance provides weighting of the backscatter intensity data for each class, reducing the misclassification caused by the lack of processing capability to fully remove the effects of water depth, angle of reflection, and other factors affecting backscatter intensity values. The signature for the flat-soft class has a low mean backscatter intensity value, low rugosity, and a high-positive covariance between backscatter intensity and rugosity; a mixed area of seafloor has a high backscatter intensity, intermediate rugosity, and high-negative covariance between backscatter intensity and rugosity; a rugose-hard area will have a low covariance between backscatter intensity and rugosity because backscatter intensity is a function of both induration and the angle of the reflecting surface relative to the position of the sonar transducer.

In high relief areas the backscatter intensities will be low downrange of high standing rocks due to shadowing. These low backscatter areas may be mis-classified as soft bottom. This problem occurs more frequently in towed systems flown close to the seafloor than in hull-mounted sonars that have higher incidence angles. A good signature for rugose rocky areas will incorporate the shadow backscatter intensity values. When rugosity is insufficient to achieve a classification that separates mixed from rugose-hard areas, the MLC stack can be augmented with a variant of backscatter such as gray-level homogeneity (Shokr 1991, Blondel 1996, Cochrane and Lafferty 2002). The backscatter intensity variant functions in the stack in the same manner as the bathymetric rugosity, as a derivative that describes change in a neighborhood around each pixel. If the backscatter-intensity data are of higher resolution than the bathymetry data, variants of backscatter intensity are useful for further delineating mixed substrate types that will have higher homogeneity values than rough rock areas.

For the design of three class signatures, small polygons were hand-drawn subjectively using the video observations and the rugosity and backscatter-intensity rasters as guidance (Fig. 3). In Fig. 3, the rugosity raster is divided into three classes using break values of 1.0001 for low, 1.0005 for medium, and higher than 1.0005 for high complexity based on discussions within the CCSWMP. The circular polygons show the approximate areas of three video observations that match the three substrate classes described above. Signatures are drawn that intersect the video observation area, and capture pixels predominantly from the appropriate rugosity class.

In this and many sonar data sets, noise in nadir results in false backscatter intensity variance and rugosity (Figs. 2 and 3) causing rugose-hard pixels in the classified raster. Fig. 4 shows the bands of trackline-coincident rugose-hard and mixed classes that result in areas known from the groundtruthing to be flat-soft bottom (video transects B and C, Fig. 2). However, strips of trackline-parallel rugose-hard in the nadir on either side of this area are undesirable if a conservative estimate of rugose-hard bottom is preferred. Adding a euclidean distance-from-nadir raster into the MLC stack, and adding an additional signature, is done by the CCSWMP to create a separate flat-soft bottom class in the nadir which is subsequently reclassified using block statistics based on adjacent non-nadir classified pixels. To eliminate the off-nadir striping that is produced because signatures have different mean Euclidean distances, the mean Euclidean distance is normalized for the non-nadir signatures. The covariance values between the Euclidean distance raster and the other layers in the classification stack are also normalized. It is also possible to create multiple signature polygons at various ranges if the data quality changes markedly as a function of Euclidean distance, rather than normalizing the distance means and covariances. Another approach to dealing with nadir and other trackline-parallel noise problems uses Fourier histogram indices as discussed by Intelmann et al. (2007).

After the substrate classification is complete the MLPA depth-zone classes are added to the raster. This is accomplished by classifying the bathymetry raster and then merging the rasters through multiplication. In this example there are three substrate classes, and two depth zones; pixels in the depth zones are assigned values of 1 (0-30 m) or 4 (30-100 m) so that the merged class values are 1, 2, 3, 4, 8, 12. Slope zones (Greene et al. 1999, Harney et al. 2006) or geomorphic zones such as canyons and pinnacles (MLPA habitats) derived from Topographic Position Indices (Iampietro et al. 2004) can also be merged into the classified raster in this manner. If stricter definition of rugosity is desired the rugosity raster can be used to reclassify those pixels that don't meet the rugosity criteria. Fig. 5 shows the substrate classes, subdivided into CDFG depth zones, with the nadir classes nulled out.

Classification accuracy assessment using the video observations is hampered by the difference in navigational accuracy of the sonar system attached to the vessel, and the tethered video sled not rigidly attached. To assess accuracy for this data set, each video observation center-point was assigned a numerical class value based on primary and secondary substrate observed. The numerical class values match the classified raster values, 1 for soft substrates such as mud-mud, 2 for mixed substrates from mud/shell to sand-rock, and 3 for rugose-hard substrates from boulder-cobble to rock-rock. Of the 172 video observations, 44% match the classified raster when compared in this manner, with a linear correlation of 0.24. It is difficult to determine if this result represents a problem with the classification or the lack of accuracy of the video point locations compounded by the rapid change in substrate over short distances. As a test of the latter a 20 meter block mean filter was applied to the classified raster, such that a floating point number ranging from 1 to 3 represented the mean of that 20 m area. A linear correlation coefficient of 0.31 was calculated for this raster. The increase in correlation suggests that video positioning is a significant problem with the accuracy assessment. Towed video-sleds cannot be tracked as accurately as ROVs deployed from stationary ships because of the increased motion and noise in the water when the ship is underway. Accurate submersible tracking technology is an added cost to a survey. Some limited groundtruthing with the best positional accuracy over areas of rapid change is worthwhile for accuracy assessment and may be done for the CCSWMP as a separate effort that includes detailed biological surveying using ROVs or submersibles.

Discussion

The classified seafloor map shown in Fig. 5 differs from previous habitat maps produced by USGS and others that are generalized polygonal products. It has the benefit of retaining the gradational changes in substrate that often occur in the benthic environment because each pixel is given a classified value, and may differ from a neighbor pixel or from the majority of neighboring pixels. It is unlike a polygon-based map where filtering is based on a minimum map unit, and hand interpretation results in discrete areas with unique values for several attributes. I addition to providing a georeferenced image of the distribution of substrate and depth in an area, the classified raster can be used in a GIS to generate summary statistical information. The simplest example is shown in Table 1, with a list of the classes, their total area, and percentage of the study area. Publishing a raster, in addition to imagery derived from the raster, will allow managers with different needs to develop final products and summary information tailored to their needs. The raster can also be combined with georeferenced fisheries information to study correlations between fish distribution and substrate (Etherington et al. 2007). As discussed in the methods section, the seafloor character raster will combine substrate, depth, and slope classes. The map produced from the raster will be color-coded to indicate the substrate and

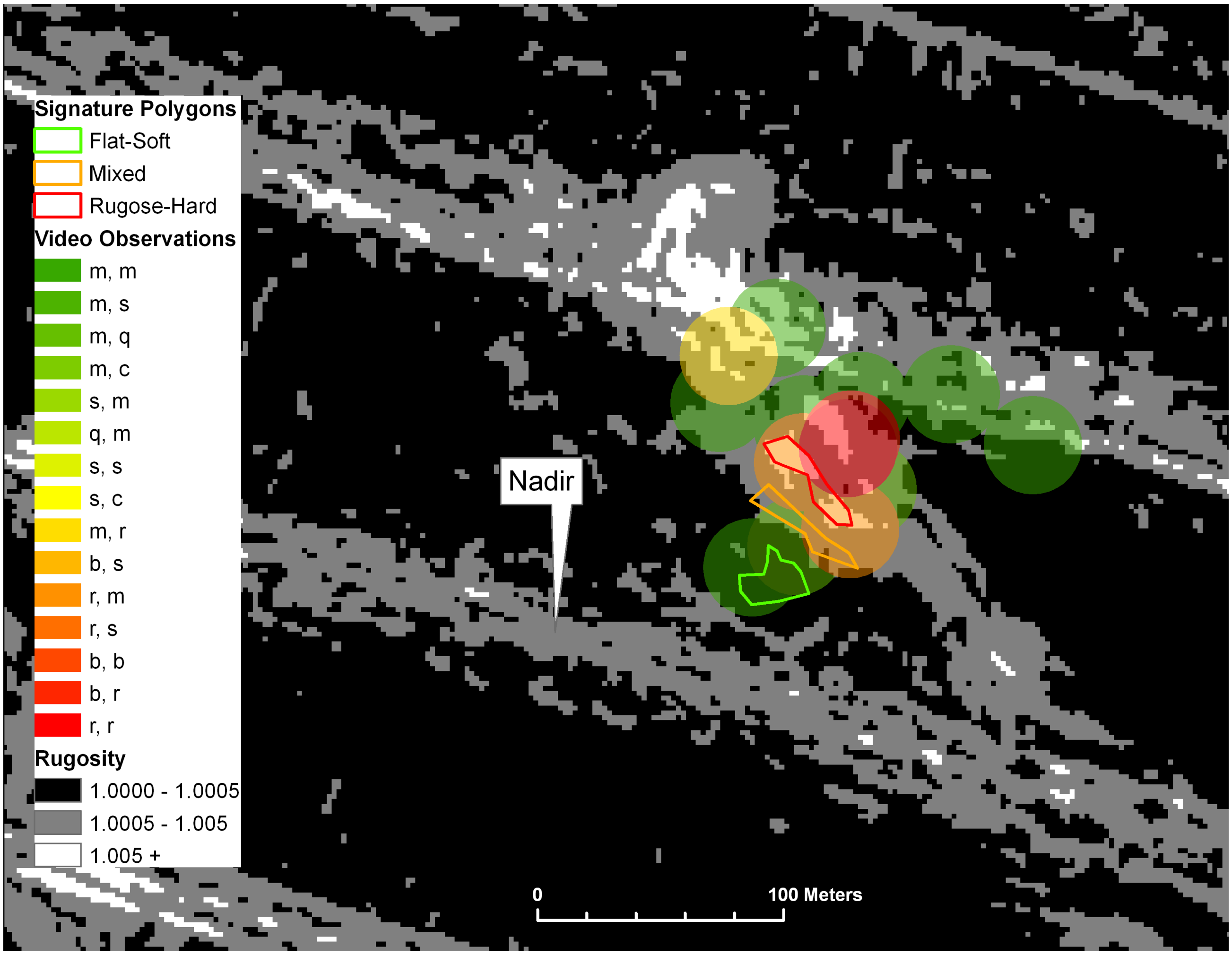

Figure 3. Classified rugosity image showing supervision polygons in the area of video transect C (see Fig. 2 for location) used for maximum likelihood classification of the study area into three substrate classes. Note the evenly spaced WNW oriented lines of high rugosity produced by noisy sonar data in the nadir area. Individual circles are 20 m diameter observation locations, colored based on primary and secondary substrate attributes. Noncircular, subjectively drawn polygons shown are similarly colored and enclose the pixels that will be used to generate the supervisory-signature statistics.

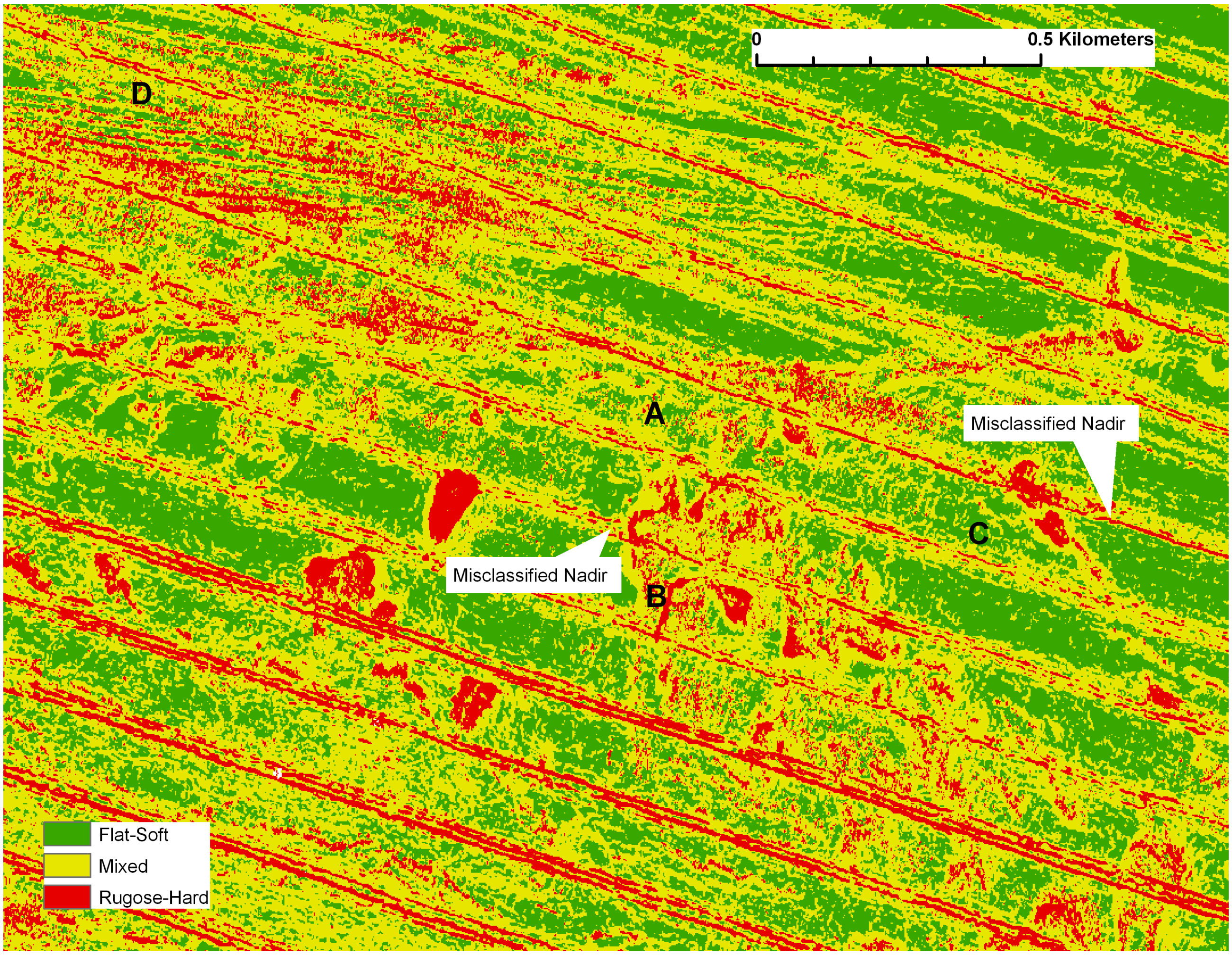

Figure 4. Image showing classified seafloor in the study area. Note how the false rugosity in the nadir seen in Fig. 3 is erroneously classified as lineations of rocky seafloor (red) in known soft sediment areas of groundtruth–video transects B and C (see Fig. 2).

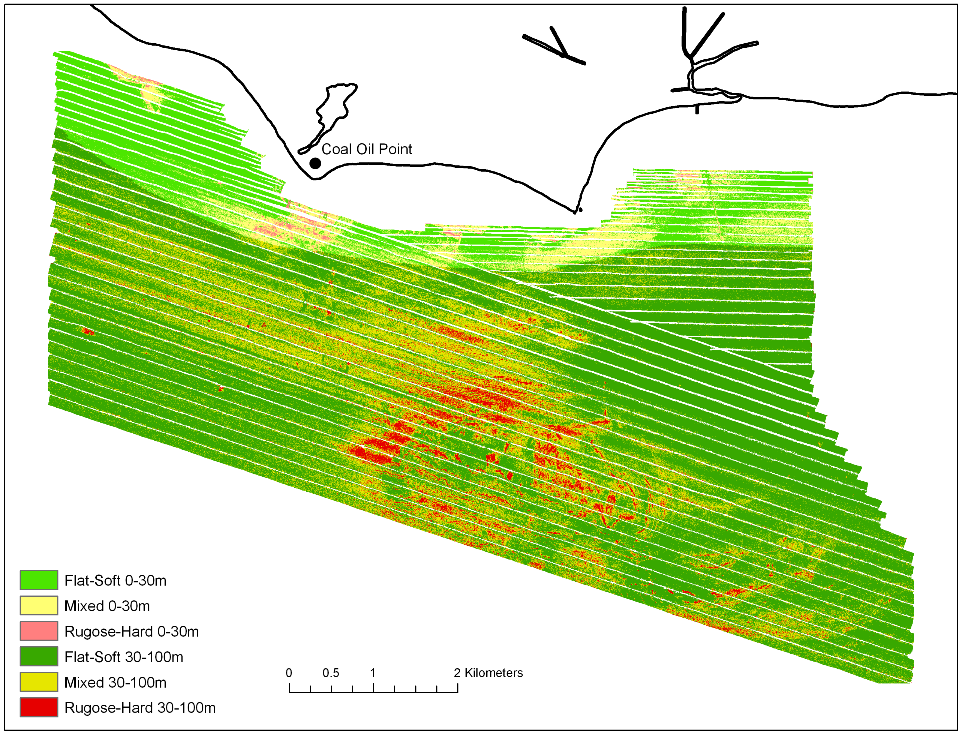

Figure 5. Seafloor character of survey area. Colors depict substrate class and California State Marine Life Protection Act (MLPA) depth zones but not slope zones.

Table 1. Area, and percentage of total area, of each substrate-depth class, found in the survey area.

Class	Area (km²)	Percentage of total area
Flat-soft 0-30 m	4.05	10.9
Mixed 0-30 m	1.61	4.3
Rugose-hard 0-30 m	0.13	0.4
Flat-soft 30-100 m	22.23	59.7
Mixed 30-100 m	7.77	20.9
Rugose-hard 30-100 m	1.42	3.8

depth classes and draped over shaded relief bathymetry to provide a visual indication of slope zones.

Products that are to be created for the CCSWMP will include both types of habitat map, and related GIS elements. The Seafloor Character Map and Polygon Habitat Map will be published as a georeferenced raster and a polygon shapefile, respectively. The habitat products will be part of an online report that includes digital maps, GIS layers, and a summary report produced for each of approximately 100 (1:24,000 scale) blocks. A mock-up of the digital map folio for one block recently presented to the COPC included 11 map sheets. The folio included gray-scale shaded relief bathymetry, color-coded bathymetry overlain on shaded relief, gray-scale backscatter intensity, gray-scale backscatter intensity overlain on shaded relief, a sheet with bathymetric perspective views of areas of seafloor with interesting geomorphology, the seafloor character map discussed in this paper, a video groundtruthing sheet with observation points overlain on the seafloor character and images from the camera sled, the polygon habitat map, a sheet showing seismic subbottom profile data, a sediment thickness isopach map, and a geologic units and structure map. Additional sheets may be added for blocks with unusual management problems, geology, or biologic features.

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